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**DIGITAL COMPUTER STUDY OF
NUCLEAR REACTOR THERMAL TRANSIENTS
DURING STARTUP OF 60-kWe
BRAYTON POWER CONVERSION SYSTEM**

by Kent S. Jefferies and Roy C. Tew

Lewis Research Center

Cleveland, Ohio 44135

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16. Abstract <p>A digital computer study was made of reactor thermal transients during startup of the Brayton power conversion loop of a 60-kWe reactor Brayton power system. A startup procedure requiring the least Brayton system complication was tried first; this procedure caused violations of design limits on key reactor variables. Several modifications of this procedure were then found which caused no design limit violations. These modifications involved (1) using a slower rate of increase in gas flow, (2) increasing the initial reactor power level to make the reactor respond faster, and (3) appropriate reactor control drum manipulation during the startup transient.</p>			
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SUMMARY

A digital computer study was made of reactor thermal transients during startup of the Brayton power conversion loop of a 60-kilowatt-electric reactor Brayton power system. A major constraint on startup of such a system is the vulnerability of the reactor to thermal stress. Thus the purpose of the study was to identify acceptable procedures for starting up the Brayton system.

A startup procedure which would require the least complication of the Brayton system was studied first. Modifications of this procedure were then studied in an effort to moderate reactor thermal transients. The startup results were evaluated with respect to design limits on critical reactor variables. These variables were peak fuel temperature, fluid temperature rise across the reactor core, outlet fluid temperature, and rate of change of inlet and outlet fluid temperature.

The Brayton system was started by using the alternator as a motor. The initial startup occurred with design gas inventory in the system; the resulting gas flow transient approximated a fast ramp to design flow. This transient exceeded the reactor design limits. When the procedure was modified so that startup occurred with only one-half of design inventory in the system, the gas flow transient approximated a slower ramp to about one-half of design flow; the reactor transients were more moderate but some of the design limits were exceeded. To stay within the limits, the ramp to half-design flow would have to last at least 10 minutes.

The severity of the reactor temperature transients could be reduced more by also increasing initial reactor power. Two methods considered for increasing the initial reactor power were: (1) use of an auxiliary heat exchanger and radiator and, (2) addition of steps in reactivity a short time before Brayton system startup. When these methods were used with the half-inventory startup procedure, no design limits were exceeded.

Another approach to moderating the reactor transients was to modify the control action during the one-half inventory startup transient. Two control methods were tried; they were (1) programmed control drum steps (open loop control) and (2) closed loop derivative control of drum position. Both methods were used with the half-inventory startup procedure; no design limits were exceeded in either case.

INTRODUCTION

Nuclear reactor power systems will be needed to generate electric power for future space missions, and the Brayton cycle is a candidate for the power conversion system. One proposed nuclear Brayton system uses a 300-kilowatt-thermal reactor with a 60-kilowatt-electric power conversion system. A schematic of this system is shown in figure 1; design temperatures and flow rates are listed on the schematic. NaK, at the

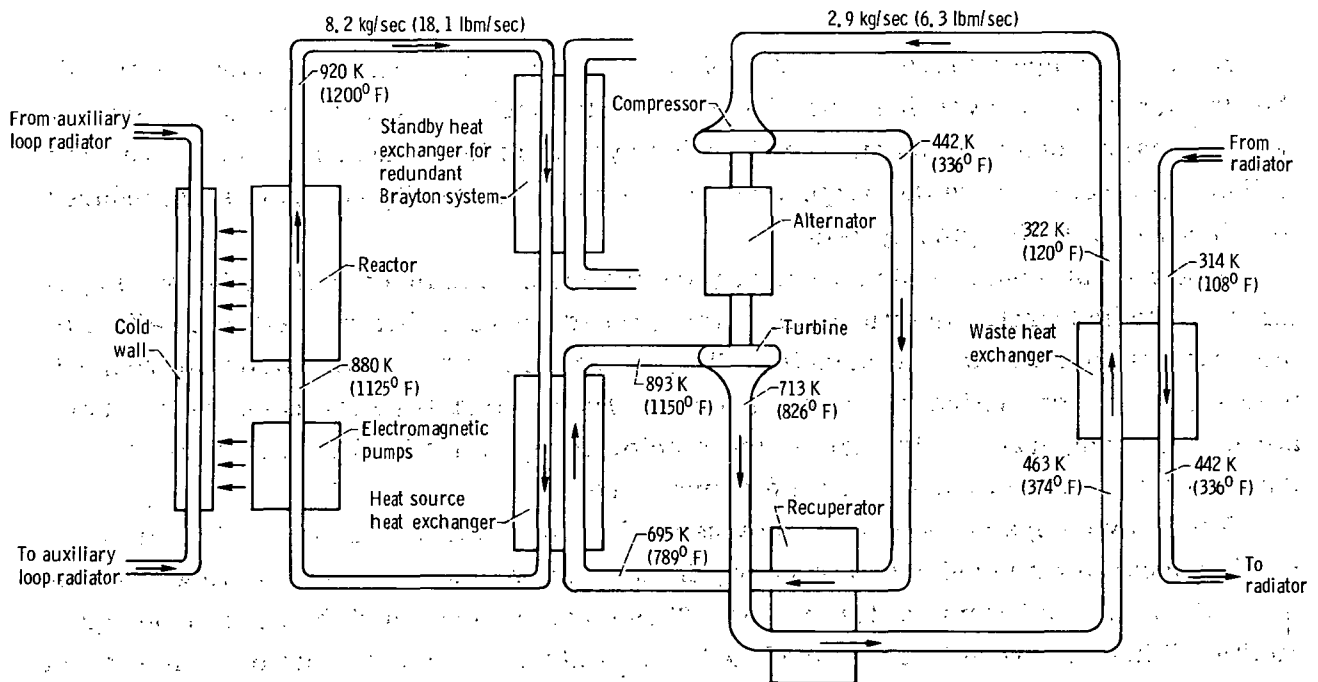


Figure 1. - Schematic of 60-kilowatt-electric reactor Brayton system.

eutectic mixture for sodium and potassium, is circulated to transfer heat from the reactor to the heat source heat exchanger. A xenon-helium mixture (molecular weight of 83.8) absorbs heat in the heat exchanger. The heated gas mixture powers a turbine-alternator-compressor unit. The closed Brayton loop is completed with a recuperator and a gas-liquid heat exchanger. The heat exchanger transfers waste heat to the radiator loop. The standby heat exchanger shown in the NaK loop of figure 1 is for a redundant Brayton system that increases power system reliability. A 2- to 10-kilowatt Brayton system which is similar to the 60-kilowatt power conversion system is described in reference 1; the 2- to 10-kilowatt system was designed for use with a solar or radioisotope heat source.

As the primary energy source of the system, the purpose of the reactor is to heat the NaK flowing through it to 921 K (1200° F). It is designed to produce 300 kilowatts of thermal power continuously during a 5-year mission. The reactor core consists of

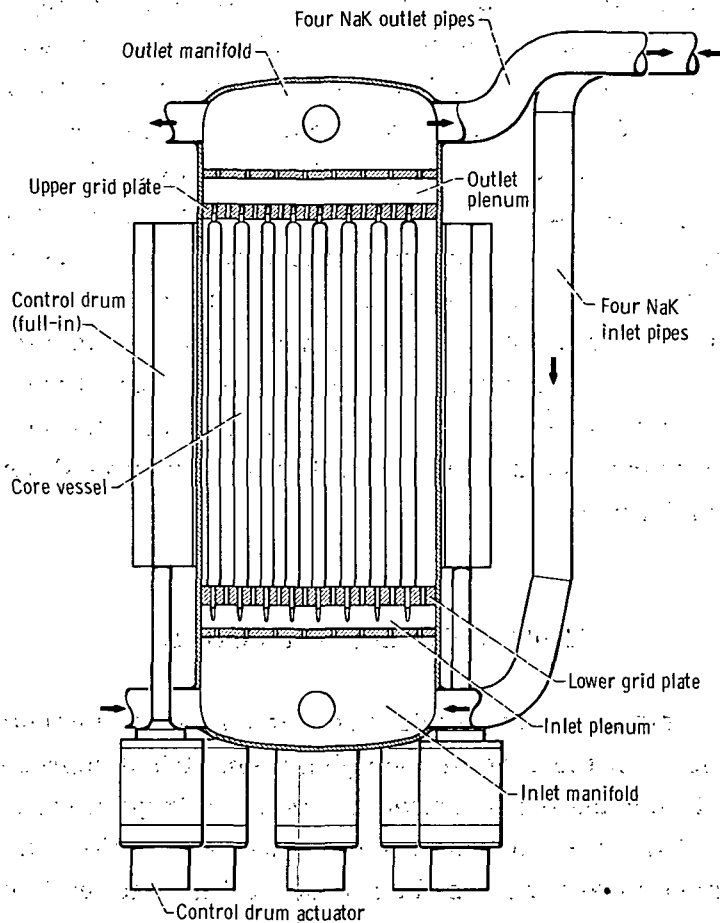


Figure 2. - Reactor assembly.

199 fuel elements held in position by two grid plates, as shown in figure 2. The control drums, which surround the reactor core, control the nucleonic reaction by reflecting neutrons back into the core. To provide an inherent power stability, the reactor core was designed to have negative temperature coefficients of reactivity through physical expansion effects. For example, an increase in power resulting in a rise in reactor temperature will expand the core structure which thereby increases the leakage of neutrons from the core and thus reduces the power back toward its original level.

Eight control drums are the only devices used to control the reactor. The drums can be moved in small steps and are used for reactor startup, for reactor control during power conversion system startup and other transients, for balancing the reactivity changes caused by fuel depletion, and for reactor shutdown. A cold wall and an auxiliary (NaK) coolant loop are used to cool the reactor control drums.

Two situations encountered in operating such a power system are startup and shut-

down. A major constraint on startup and shutdown of the reactor is its vulnerability to thermal stress and the Brayton system must recognize this limitation. Emergency shutdown transients have been simulated on the digital computer; these results were reported in reference 2. Various startup procedures have also been simulated on the digital computer. The startup results, reported herein, evaluate the effect of power conversion loop startup procedure on the severity of reactor thermal transients.

In the startup study, a relatively simple startup procedure was studied first. Modifications of this procedure were then studied in an effort to reduce the reactor thermal transients. The startup results were evaluated with respect to maximum limits on critical reactor variables. These variables were peak fuel temperature, temperature rise across the reactor, outlet temperature and rate of change of inlet and outlet temperature. Peak reactor power was also considered in the evaluation although a design limit on power had not been defined.

DIGITAL COMPUTER MODEL

The primary analysis tool used in this study was a digital computer model which included a detailed model of the reactor loop plus a simplified representation of the gas loop. This model will hereinafter be called the reactor Brayton model. A second more detailed model of the gas loop was used to generate gas flow startup transients. These gas flow transients were then used as inputs to the reactor Brayton model.

Reactor Brayton Model

A schematic of the components simulated is shown in figure 3. The simulation included the reactor, the Brayton heat source heat exchanger and the standby Brayton heat source heat exchanger. Pipe line delays in the NaK loop were simulated, but the pipe heat capacity was neglected because it was small compared to the NaK heat capacity. Pipe line delays in the gas loop including the effects of pipe heat capacity were simulated.

The turbine and recuperator were represented by extremely simple models. The outlet temperature from the turbine was approximated by a linear function of turbine inlet temperature. The temperature out of the recuperator (going to the heat source heat exchanger) was assumed to follow the turbine outlet temperature (minus a small ΔT) as a first-order lag. These approximations yielded temperature transients sufficiently similar to those generated by the previously mentioned gas loop model to justify their use in this study of reactor transients.

The heat source heat exchanger model was a 10-lump representation of heat transfer

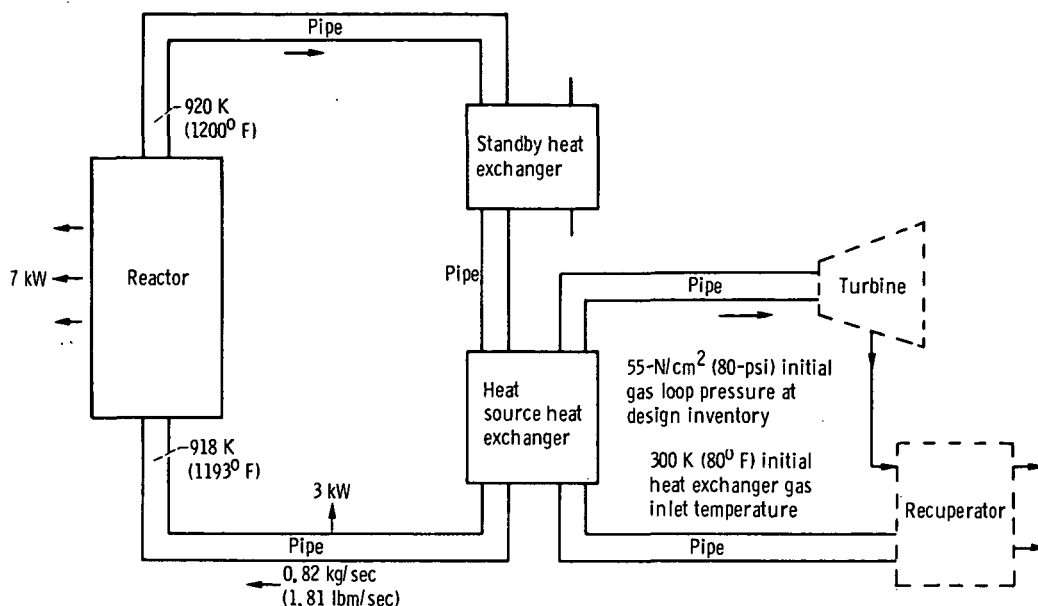


Figure 3. - Simulated components and initial conditions.

dynamics. Liquid metal, metal, and gas temperature were computed for each lump. The liquid metal and metal temperature computations included the effect of heat energy storage within the lumps. The computed gas temperature distribution did not account for heat storage because very little energy is stored in the gas.

Because the cold wall has considerable thermal mass, the temperature changes of the auxiliary loop occur too slowly to significantly influence the startup transients. Therefore, this loop was not simulated, although a power loss to the cold wall was simulated.

The reactor model was the most important part of the system model for the transients studied. Briefly, the reactor model included (1) a calculation of excess reactivity as a function of temperature and control drum position, (2) a simulation of reactor power dynamics including six delayed neutron groups, (3) a sinusoidal distribution of reactor power axially within the core, (4) first-order lag representations of the thermal capacities of the manifolds, plenums, and grid plates, and (5) a 20-lump model (along the flow direction) representing the heat transfer dynamics in the core. Conduction of heat along the flow axis was neglected.

A more complete description of the reactor model is given in the emergency shutdown report (ref. 2). The model of reference 2 includes a calculation of reactor decay heat following shutdown which was not included in the model for the startup study. Constants used in the system model such as heat capacities, heat transfer coefficients, inventories, and so forth, are also given in reference 2.

Gas Loop Model

The gas loop model generated the gas flow transients used as inputs to the reactor Brayton model and the temperature transients used to check the simplifying assumptions of the Brayton part of the reactor Brayton model. The gas loop model included dynamic models of the turbine, alternator, compressor, and heat exchangers. In generating the gas flow startup transients, liquid flow in the radiator loop was assumed constant at the design value; liquid temperature into the waste heat exchanger was also constant at the design value of 314 K (114° F). Reactor loop flow and temperature into the heat source heat exchanger were assumed constant at their design values of 8.2 kilograms per second (18.1 lbm/sec) and 920 K (1200° F), respectively. Thus, the feedback effects of the reactor loop and the radiator loop on the gas flow startup transient were not included.

Normal Reactor Control

During normal reactor operation, the reactor coolant outlet temperature is within a range (deadband) of 913 to 933 K (1185° to 1220° F). Moderate disturbances, such as long-term fuel depletion, cause the coolant temperature to drift outside of the temperature range. If the temperature drifts below 913 K (1185° F), a neutron reflector control drum is stepped slightly inward (positive reactivity). This causes reactor power to increase. The increased power causes reactor coolant outlet temperature to increase. If the outlet temperature has not returned to the deadband range after 1 minute, drum steps continue at 1-minute intervals. Likewise, if the outlet temperature drifts above 933 K (1220° F), the control drums are stepped outward (negative reactivity). The reactivity worth of each control drum is between 0.5 and 1.3 cents per step. The step worth depends on the angular position of the control drums. A worth of 0.5 cent per step was used for the computer transients reported herein.

POWER CONVERSION SYSTEM STARTUP PROCEDURE

Startup Procedure for Reactor Brayton Model

Before the start of gas flow, the reactor was in equilibrium, and its power was assumed to be 10 kilowatts; the 10 kilowatts included a 7-kilowatt loss from the control drums to the cold wall and a 3-kilowatt pipe radiation loss. In addition, the NaK flow was assumed to be at 10 percent of design or at 0.82 kilogram per second (1.81 lbm/sec). Initial conditions for other pertinent variables are given in figure 3. With these

initial conditions, startup was initiated by increasing the NaK flow and gas flow simultaneously. The NaK flow was ramped from 10 percent of design to design in 1/2 second. The input gas flow rate startup schedule was, in each case except one, a ramp approximation of a flow schedule generated by the gas loop model. These NaK flow and gas flow transients were the inputs to the reactor Brayton model.

Gas Flow Startup Transient

The gas loop model was used to simulate two gas flow startup transients. The startup procedure was the same in both cases except design gas inventory was assumed in one case and half of design inventory in the other case.

In this simulation the alternator was used as a motor; it was connected to a power source operating at one-third of the alternator design frequency. The power source was removed when the turbine-alternator-compressor speed reached one-third of its design value. The power input to the turbine was at that point sufficient to drive the rotating unit's speed up to its design value of 24 000 rpm. This speed corresponds to a design flow rate of 2.9 kilograms per second (6.3 lbm/sec) when design inventory is in the system. If only half of design inventory is in the system, the final flow rate is about half the design value and the rate of flow increase is less.

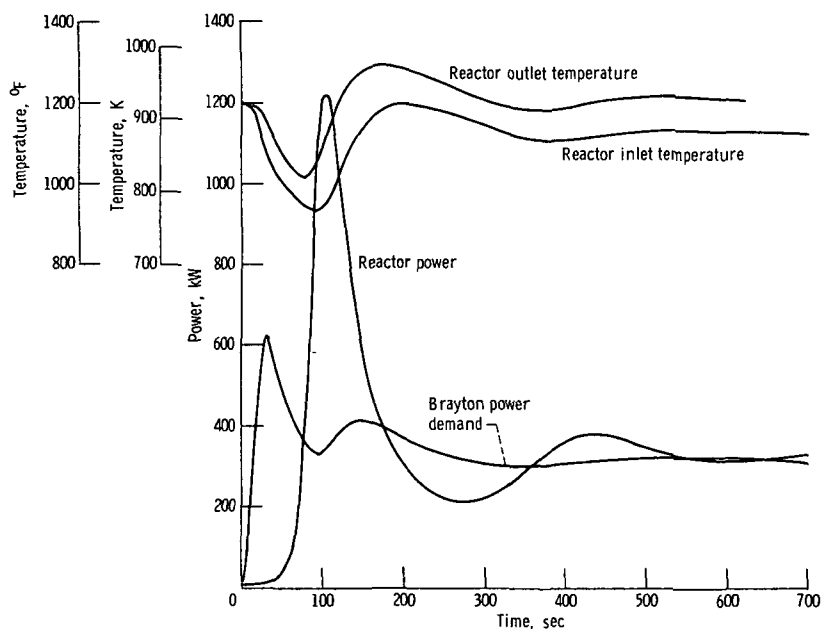
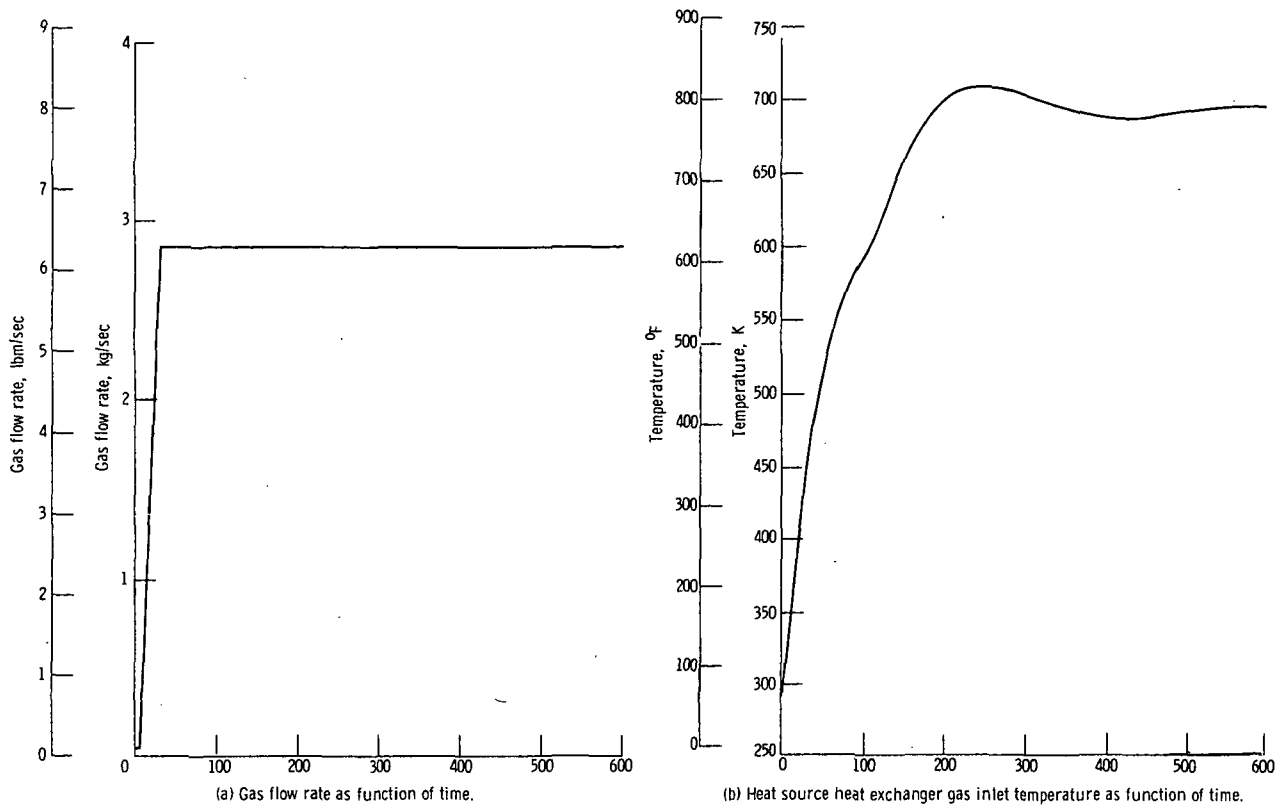
RESULTS AND DISCUSSION

The results of the full-inventory startup, are discussed first; this startup exceeded design limits on reactor critical variables. Then the results of various modifications of the full-inventory startup are discussed.

Full-Inventory Startup

A ramp approximation of the full-inventory gas flow transient was used with the reactor Brayton model startup procedure for this startup. The gas flow transient and the resulting gas temperature into the heat source heat exchanger are shown in figure 4(a) and (b), respectively. These two variables plus the outlet gas temperature determine the thermal power absorbed by the gas flowing through the exchanger. This thermal power, hereinafter called the Brayton power demand, is shown in figure 4(c). The reactor power and the reactor inlet and outlet temperatures are also shown in figure 4(c).

The response of reactor power to the rise in power demand is relatively slow at the low initial power level (10 kW), but after about 50 seconds, it starts to rise sharply and



(c) Reactor power, Brayton power demand, and reactor fluid temperature transients.

Figure 4. - Full-inventory startup.

overshoots the power demand by about 300 percent (to 1219 kW). The excess power then drives the reactor temperatures above their normal range. The transients in power and temperature gradually die out during the remainder of the run.

The maximum values of the critical reactor variables are compared with the corresponding safety limits in table I. The rate of change of NaK inlet temperature exceeded its design limit of 2.8 K per second (5° F/sec) by about 1 K per second (2° F/sec) during the gas flow ramp to design. The reactor outlet temperature exceeded the design limit of 950 K (1250° F) by about 20 K (36° F); the maximum occurred at approximately 180 seconds, which was the end of the reactor power excess over the Brayton power demand. The NaK temperature difference from reactor core inlet to reactor core outlet reached 117 K (210° F) or about double the design limit; this maximum occurred near the peak in reactor power. The maximum fuel temperature along the axis of the fuel rod exceeded its design limit of 1032 K (1400° F) by 44 K (80° F). Therefore all specified design lim-

TABLE I. - COMPARISON OF CRITICAL REACTOR VARIABLES WITH SAFETY LIMITS FOR ALL STARTUPS

Run description	Critical variable (safety limit)								
	Maximum rate of change of NaK temperature (2.8 K/ sec or 5° F/sec)		Maximum NaK outlet temperature (950 K or 1250° F)		Maximum NaK temperature difference across core (311 K or 100° F)		Axial maximum core temperature (1032 K or 1400° F)		Maximum reactor power (limit undefined), kW
	K/sec	°F/sec	K	°F	K	°F	K	°F	
Full-inventory startup (fig. 4)	3.8	6.9	968	1286	372	210	1075	1480	1219
Half-inventory startup (fig. 5)	2.0	3.6	968	1286	325	125	1024	1384	725
10-Minute gas flow ramp to one-half design flow (fig. 6)	.7	1.3	948	1248	289	61	977	1302	325
Startup with auxiliary heat exchanger (fig. 7)	1.1	2.0	948	1247	301	82	990	1322	409
Startup after reactivity addition (fig. 8)	1.0	1.8	938	1230	304	87	980	1305	433
Startup with open-loop drum control (fig. 9)	1.4	2.6	927	1211	309	97	957	1264	538
Startup with closed-loop drum control - high reactivity per step (fig. 10(a))	1.4	2.6	940	1233	302	83	977	1300	412
Startup with closed-loop drum control - low reactivity per step (fig. 10(b))	1.4	2.5	935	1225	295	71	960	1280	320

its were exceeded. Although no design limit has been established for reactor power, the overshoot to 1219 kilowatts is considered to be unacceptable.

Since the full-inventory startup caused all the specified design limits to be exceeded, it was necessary to consider modifications of the procedure. The approach used was to look for modifications which would minimize the difference between reactor power and Brayton power demand. A better match between these powers could be expected to moderate the reactor thermal transients. A look at the early portion of the power plots in figure 4(c) suggests two methods to improve the match between the two powers:

- (1) Slowing down the rate of increase in Brayton power demand (by slowing the rate of increase in gas flow)

- (2) Making the reactor respond faster to the rise in power demand

Both methods were studied and the results are discussed in the following sections.

Slower Gas Flow Startup

The rate of increase of gas flow can be slowed by starting with less than design inventory when the alternator is to be motored; design speed is then reached at a flow rate less than design. An inventory of about one-half design provides sufficient flow to make the reactor Brayton system self-sustaining for such a startup. Then, once the transients have settled out sufficiently, gas can be bled into the loop until design inventory and flow are reached. Such a half-inventory startup was simulated by using the half-inventory gas flow transient with the reactor Brayton model startup procedure.

Half-inventory startup. - The gas flow and temperature into heat exchanger transients are shown in figures 5(a) and (b), respectively. The flow ramps to about one-half of design flow rate, and the ramp is slower than for the full-inventory flow transient. The beginning of a slow ramp from one-half of design to design flow rate is also shown starting at 550 seconds in figure 5(a); the reactor transients for the remainder of the ramp were not significant and are therefore not shown. Reactor power, Brayton power demand, and reactor inlet and outlet temperatures are shown in figure 5(c). The peak Brayton power demand is reduced from over 600 kilowatts for the full-inventory startup to about 300 kilowatts. As a result the peak reactor power is reduced from 1200 to 700 kilowatts. Reactor temperature transients are also less severe than for the full-inventory startup. The maximum values of the key reactor variables for this and all other startups are compared with the design limits in table I. For this startup the maximum rate of change of temperature and the maximum fuel temperature were within their design limits. However, maximum reactor outlet temperature exceeded its limit by 19 K (35° F) and the temperature difference across the core exceeded its limit by 14 K (25° F). The design limits used in this report are probably conservative. The half-inventory startup would be acceptable if the reactor safety limits were slightly more

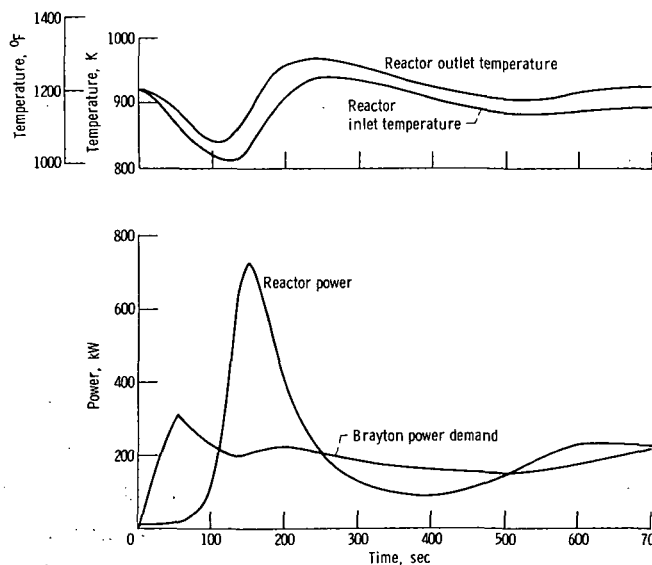
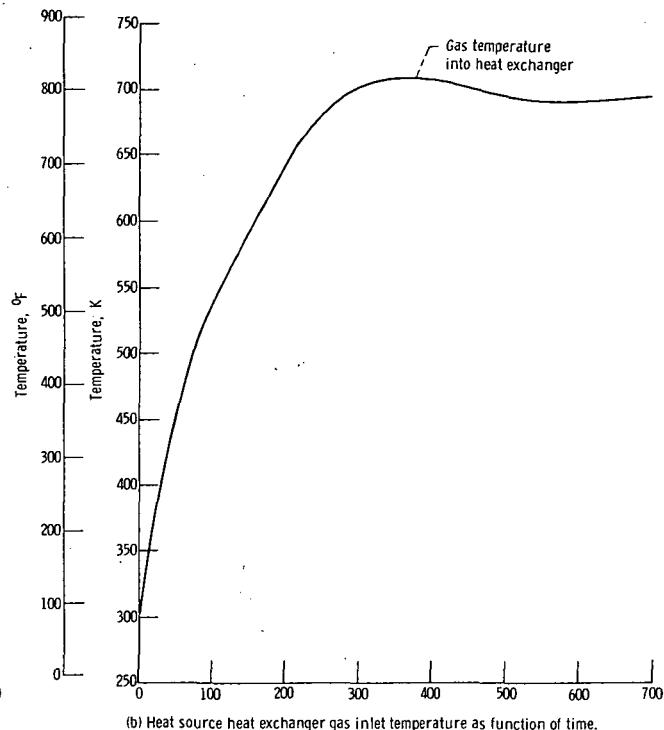
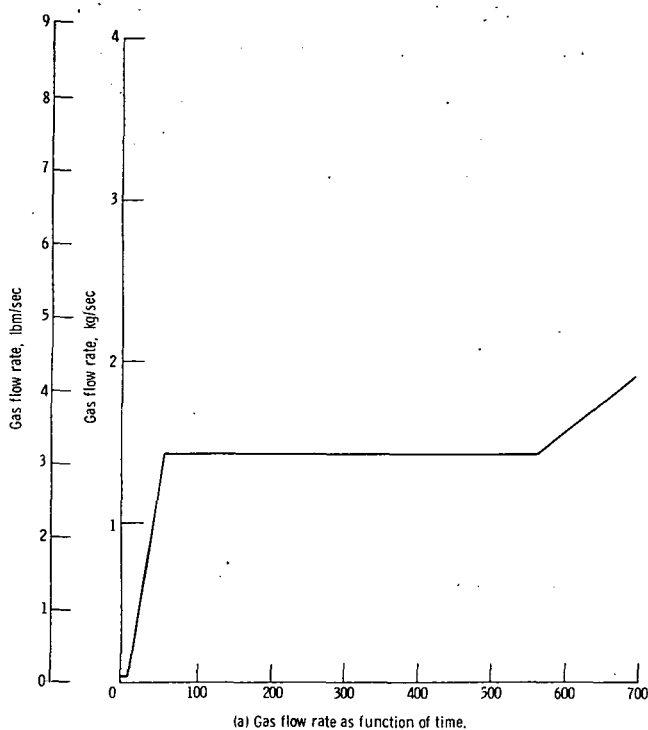


Figure 5. - One-half inventory startup.

lenient.

Ten-minute ramp startup. - It was found that none of the reactor design limits were exceeded if the gas flow ramp from zero flow to one-half design flow had a duration of 10 minutes or more. Plots of reactor variables and power demand that were obtained by using such a ramp with the reactor Brayton model startup procedure are shown in figure 6. The disadvantage of using such a ramp is that it could not be achieved with the previously described alternator motoring procedure; thus system complications would be required in order to approximate such a ramp. For example, a variable frequency pow-

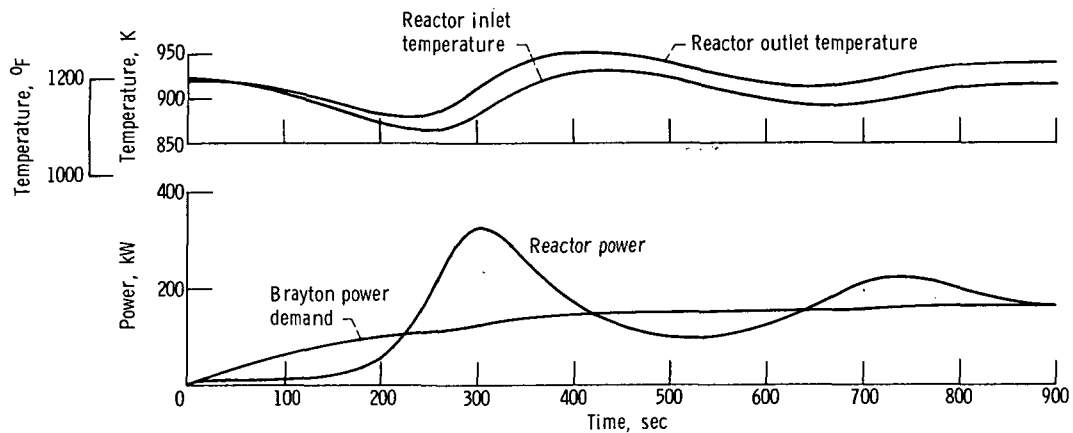


Figure 6. - Ten-minute gas flow ramp to one-half of design flow.

er source for motoring the alternator or controlled injection of gas inventory might be used. Also a special gas supply to the bearings would have to be provided to prevent metal to metal contact for an extended period of time.

Making Reactor Power Respond Faster

Two approaches to making the reactor respond faster were studied. The one-half inventory gas flow ramp plotted in figure 5(a) was used in the runs that evaluate these approaches. The first approach was to raise the initial power level of the reactor since it is characteristic of the reactor to respond faster at higher power levels. The second approach was to manipulate the control drums during the transient.

The initial reactor power can be increased by using an auxiliary heat exchanger and radiator or by inserting control drum steps in reactivity a short time before the gas flow transient begins. Both methods were studied.

Startup with auxiliary heat exchanger. - The startup procedure used was similar to that used with the half-inventory startup. The differences were:

(1) Initial reactor power was 110 kW instead of 10 kW. It was assumed that the additional 100 kW was being dissipated by use of an auxiliary heat exchanger and radiator; the auxiliary heat exchanger was assumed to be located between the two other reactor loop heat exchangers.

(2) The flow of coolant through the auxiliary heat exchanger and the power being dissipated by the auxiliary heat exchanger were stepped to zero as the gas flow transient began.

The startup results are shown in figure 7. Reactor power has a substantial head start

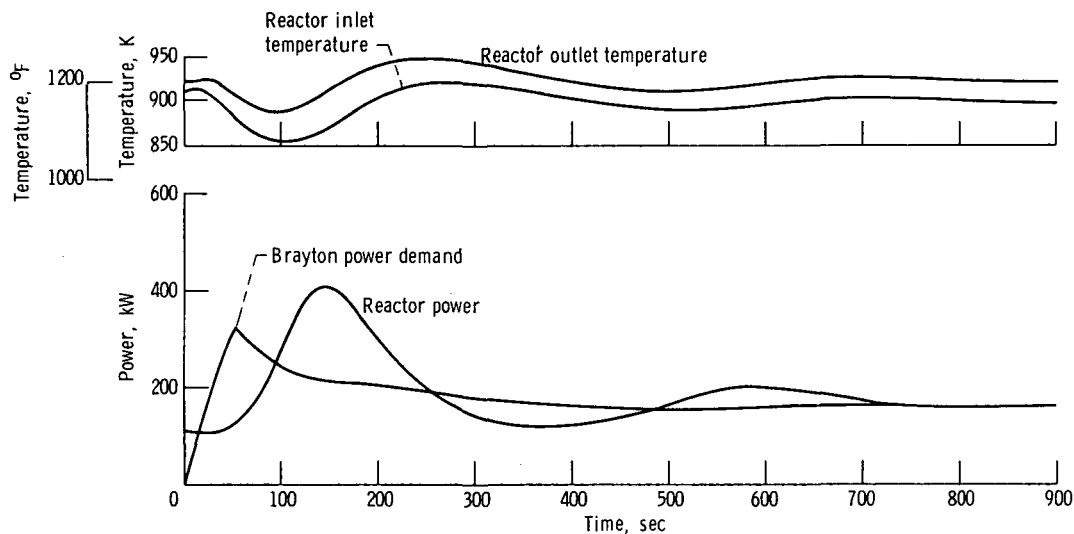


Figure 7. - Startup with auxiliary heat exchanger.

on power demand by being at high initial power level and also responds faster. The improved match between the powers results in more moderate transients and no design limits were exceeded. The disadvantage of this method is that the addition of an auxiliary heat exchanger and radiator represents a major increase in system complexity.

Startup after reactivity addition. - A higher initial power level can be achieved by adding control drum steps in reactivity before the gas flow transient begins. This procedure was used for the run shown in figure 8. It is seen that the initial reactor outlet temperature was 56 K (100° F) below the design value to allow for an increase in temperature when reactivity is added. During the first 90 seconds, drum steps (0.5 cent/step) are added at 3-second intervals for a total of 30 steps. The reactor power rises to 110 kilowatt at 200 seconds as a result of the increased reactivity; at this time the NaK flow ramp and the half-inventory gas flow transient begin. Again, no design limits were exceeded. The resulting transients are, however, somewhat sensitive to the time the gas flow transient begins. If the gas flow ramp had not begun at 200 seconds, the reactor power would have peaked at about 110 kilowatts as a result of increased temper-

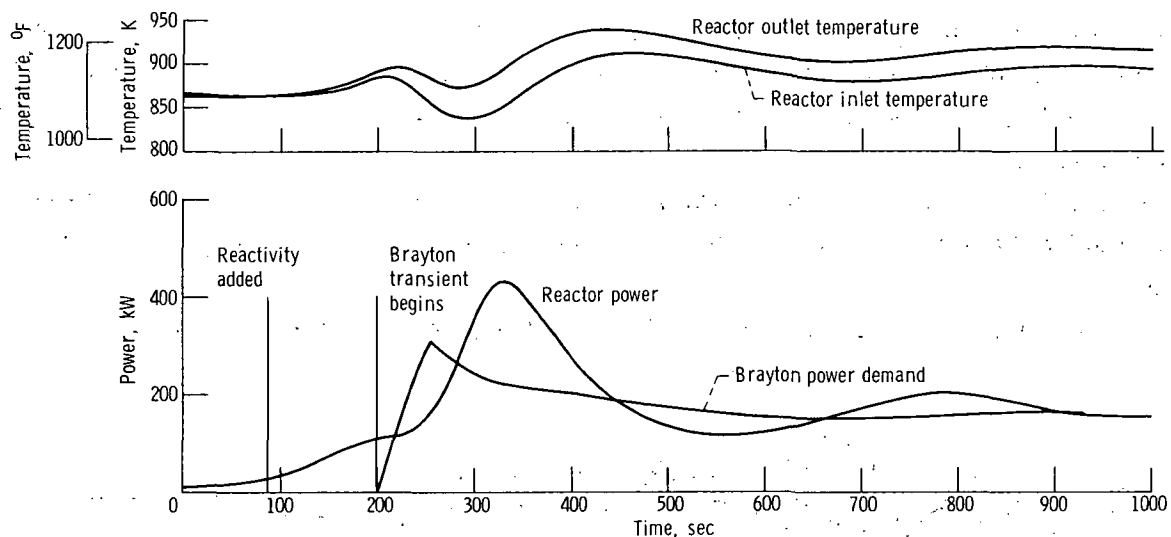


Figure 8. - Startup after reactivity addition. 0.5-Cent steps in reactivity were added at 3-second intervals between 0 and 90 seconds for total of 30 steps.

ature. The flow transients need to begin when the reactor power is peaking to get the full benefit of the method.

Two methods of speeding reactor response by manipulation of the control drums during the startup transient were studied. The first method was open-loop (or programmed) manipulation of drum position. The other was closed-loop (feedback control) manipulation of drum position. In both cases the startup procedure was the same as for the half-inventory startup except for the drum manipulation that took place during the transient.

Open-loop control. - Programmed control drum steps were used to limit the power overshoot for the run of figure 9. The initial drop in reactor temperatures causes reactor power to increase. The effect of the drop in temperature is partly counterbalanced by stepping the control drums to remove reactivity at the beginning of the transient; drum steps with a reactivity value of -0.5 cent per step are made at 3-second intervals during the first 90 seconds for a total of 30 steps. As a result, peak reactor power is about 180 kW less than for the half-inventory startup. The control drums are then stepped to re-insert reactivity when the increasing reactor temperatures would otherwise be driving the power below the steady-state value; steps are made (+0.5 cent/step) at 3-second intervals during the 90-second period starting at 280 seconds for a total of 30 steps. The reactor variables all remain within their design limits although the maximum fuel temperature difference is only 2 K (3° F) less than the limit. A disadvantage of this procedure is that its success is sensitive to the timing of the reactivity insertion. Appropriate timing requires accurate knowledge of system dynamic characteristics.

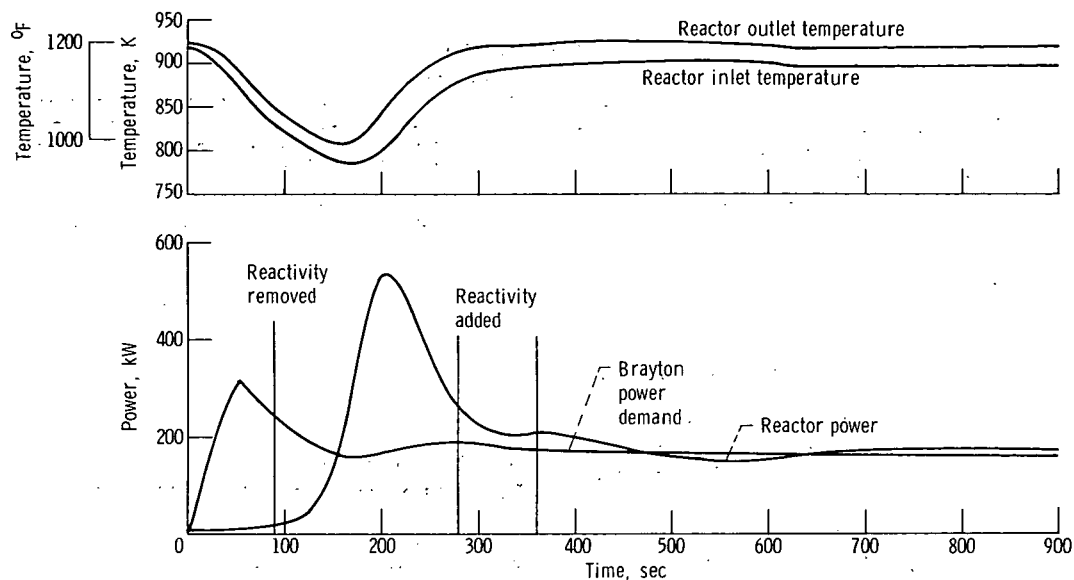
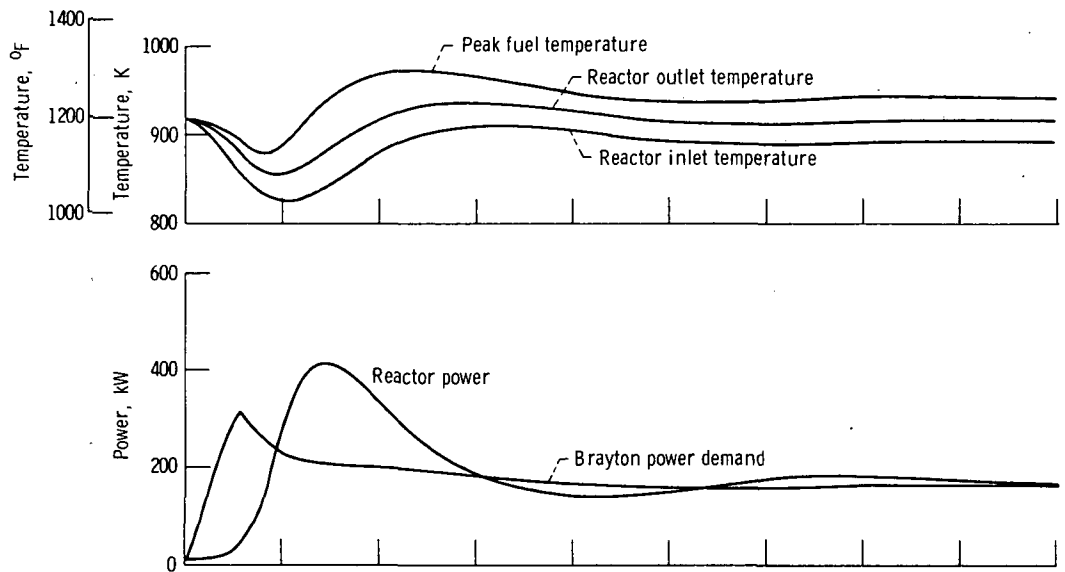


Figure 9. - Startup with open-loop drum control. 0.5-Cent steps in reactivity were removed at 3-second intervals between 0 and 90 seconds for total of 30 steps. 0.5-Cent steps were added at 3-second intervals between 280 and 370 seconds for total of 30 steps.

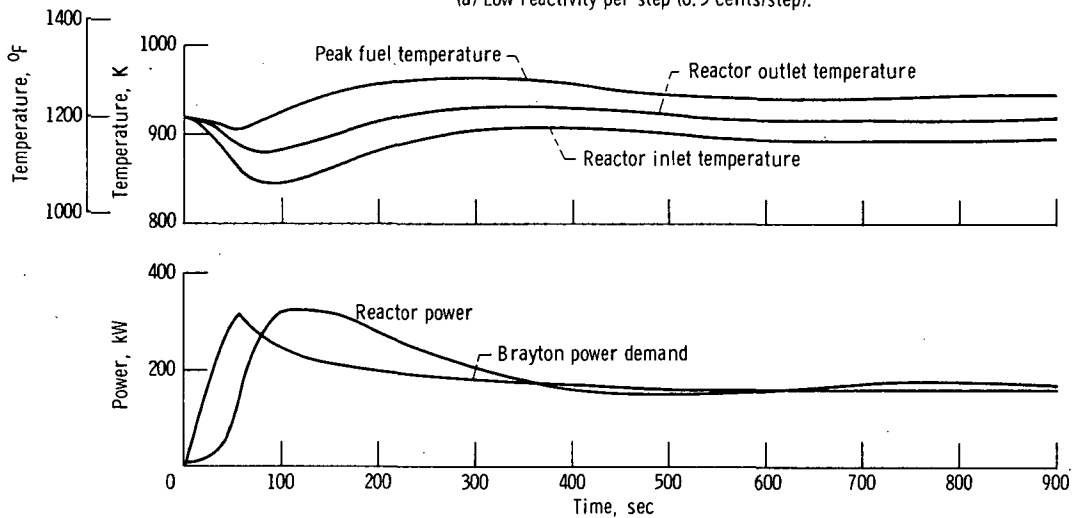
Closed-loop derivative control. - An unpublished analysis by Donald R. Packe in 1962 at Lewis Research Center indicated that satisfactory reactor startup control for a reactor Rankine system (SNAP-8) could be obtained if the control action were proportional to the derivative of the outlet temperature. Therefore, this control was evaluated for the reactor Brayton system. Two startups were simulated with this type of control. The low value of reactivity per step (0.5 cent/step) was used for one run and the high value of 1.3 cents per step was used for the other. The proportionality constant used for corrective action (the feedback gain) was 21.6 steps per K per second (12 steps/°F/sec); that is, the control modified the built-in reactivity by the addition (or subtraction) of 21.6-steps-per-K-per-second (12-steps/°F/sec) change in outlet temperature. The results of these two startups are briefly summarized as follows:

(1) Low reactivity per step - The startup results are shown in figure 10(a). Peak reactor power was reduced from about 700 kilowatts for the half-inventory startup to about 400 kilowatts. No design limits were exceeded.

(2) High reactivity per step - The results for this startup are shown in figure 10(b). Here the peak reactor power of 325 kilowatts is only about 10 kilowatts more than the peak power demand. The maxima of all the key reactor variables were reduced as a result of the increased reactivity worth per step. Although this approach appears to be a good one, it has the disadvantage of increasing the complexity of the control apparatus.



(a) Low reactivity per step (0.5 cents/step).



(b) High reactivity per step (1.3 cents/step).

Figure 10. - Startup with closed-loop drum control.

CONCLUDING REMARKS

The original startup procedure studied yielded reactor temperature transients which exceeded all the proposed design limits. However, several modifications of this procedure were found which yielded transients with no design limit violations.

In the original procedure, startup occurred with design gas inventory in the system, and the resulting gas flow transient approximated a fast ramp to design flow. With one-half of design inventory in the system, the gas flow transient approximated a slower ramp to about one-half of design flow. With this modification, the reactor transients

were more moderate but some safety limits were exceeded. The half-inventory startup would be acceptable if the reactor design limits were slightly more lenient. It was found that a 10-minute gas flow ramp from zero flow to one-half of design flow was the fastest ramp that did not exceed any design limits; significant system complications would be required, however, in order to achieve a startup with such a ramp.

The severity of the reactor temperature transients could also be reduced by increasing initial reactor power. Two methods considered for increasing the initial reactor power were: (1) use of an auxiliary heat exchanger and radiator and (2) control drum steps to increase reactivity a short time before Brayton system startup. When these methods were used with the half-inventory startup procedure, no design limits were exceeded. Of the two methods, control drum steps requires much less system complication. This method has the disadvantage, however, that startup must be timed to match the peak of reactor power.

Another approach to moderating the reactor temperature transients was to modify the control action during the startup transient. Two control methods were tried; they were: (1) programmed control drum steps (open-loop control) and (2) closed-loop derivative control of drum position. Both techniques were used with the half-inventory startup procedure; no design limits were exceeded in either case. With the closed-loop derivative control, the design margins were especially good.

From a performance viewpoint, the closed-loop derivative control (with half-inventory procedure) was the most promising approach to the startup problem. Such a modification, however, would increase the complexity of the control apparatus.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 24, 1973,
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